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ABSTRACT

A series of field and laboratory tests were conducted to evaluate the accuracy of in-situ thermal resistance measurement techniques. The results of thermal performance evaluation of the exterior walls of six thermal mass test houses situated in Gaithersburg, Maryland are presented. The wall construction of these one-room houses includes insulated light-weight wood frame, uninsulated light-weight wood frame, insulated masonry with outside mass, uninsulated masonry, log, and insulated masonry with inside mass. In-situ measurements of heat transfer through building envelopes were made with heat flux transducers and portable calorimeters. A sufficiently long period of measurements, depending on the thermal mass of wall structure, is needed to provide reliable thermal resistance data. The comparisons of the results from these field measurements with those derived from sections of the same wall structures tested in a guarded hot box facility in a laboratory are presented. A well-insulated, double-stud test wall was also tested under simulated thermal conditions including steady-state and periodically varying outdoor temperature using a calibrated hot box and the in-situ measurement procedures.

From these test results, the in-situ methods are shown to provide thermal resistance data within 9% of the hot box results. The extent of variability in wall resistance values measured by a single calorimeter or heat flux transducer is found to range from 0.3 to 9% with an average of 4%.

Key Words: Building, exterior envelope, field test, heat flux, in-situ measurements, temperature, thermal resistance, portable calorimeter, wall.

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1. INTRODUCTION

The thermal performance of a building envelope has a great impact on both heating and cooling fuel costs and on maintenance expenditure for a building. This necessitates increased attention to the design and construction of more thermally efficient envelopes, and the retrofit of existing buildings. Quantitative information about the thermal performance of exterior envelopes under actual use conditions is required for various purposes including assessing the effectiveness of energy conservation measures, and estimating peak heating and cooling load for the sizing of heating, ventilation and air-conditioning equipments.

Measured thermal resistance for building materials or components available for design of building envelopes have been largely derived from carefully prepared test specimens constructed for the sole purpose of obtaining measurements in a laboratory facility under controlled conditions. However, those test specimens may not adequately reflect conditions in the field, such as substandard workmanship, defective insulation, and deterioration of building components caused by materials aging and moisture penetration. Also, the prescribed exposure conditions in the laboratory tests may differ from the actual exposure in the field due to dynamic variations of ambient temperature and solar radiation. Due to the continuing development of construction techniques and new types of building materials, there is a need to obtain data on thermal resistance of building components under actual use conditions. Field thermal measurements can also provide information about whether the thermal performance of building components meets thermal design specifications and can be used for comparison with theoretical predictions of computer simulation models.

Though the results of field measurements using heat flux transducers and portable calorimeters have been reported in the literature [1-4], little experimental work has been done to assess the accuracy of these in-situ measurement techniques. This is primarily due to the lack of knowledge regarding the heat flow characteristics of the wall sections in these tests.

This paper compares the results of in-situ methods for measuring thermal resistance values of exterior walls of six test houses to the results obtained in a guarded hot box on identical wall structures. The walls tested are insulated light-weight wood frame, uninsulated light-weight wood frame, insulated masonry with outside mass, uninsulated masonry, log, and insulated masonry with inside mass. In addition, a highly insulated wall was tested both by in-situ methods and in the NBS calibrated hot box.

2. DESCRIPTIONS OF TEST BUILDINGS

Field thermal measurements were carried out on six one-room test buildings that had the same floor area and orientation, and were identical except for the wall construction. These buildings, situated in Gaithersburg, Maryland, had previously been used to investigate the effect of wall mass on space heating and cooling loads and indoor comfort of residential buildings [3]. Each building had a different wall structure as mentioned before. A detailed description of the wall construction of these test buildings is given in Table 1.

Each test building had a 20 x 20 ft. (6.1 x 6.1 m) concrete floor covered with 2 in. (51 mm) thick polystyrene foam insulation board, and a pitched roof with a gypsum board ceiling located 90 in. (2.29 m) above the floor. In the attic space, 11 in. (280 mm) thick, R-34 $h \cdot ft^{2} \cdot {}^{o}F/Btu$ (R-6.0 $m^{2} \cdot K/w$) glass fiber blanket insulation was installed over the ceiling. Two double hung, single glazed windows with exterior storm sash, norminal size 35 x 44 in. (0.89 x 1.12 m) were situated on both the south-facing and the north-facing walls, and a 19.5 ft^2 (1.81 m^2) insulated metal door was located on the east wall of each test building. The indoor air of each test building was conditioned by a centrally located 4.1 kW electric forced air heating plant equipped with a 13,000 Btu/h (3,800 W) split-unit vapor-compression air conditioning system.

3. INSTRUMENTATION AND MEASURING TECHNIQUE

To obtain the wall thermal resistance data, measurements are required of the heat flux through an exterior wall and the air-to-air temperature difference across the wall. The heat flow rate was measured with heat flux transducers and portable calorimeters. The heat flux transducer consisted of a 4 in (102 mm) diameter, flat circular wafer containing an embedded thermopile with its hot and cold junctions attached to the internal wafer surfaces. The thermopile produced a voltage signal directly proportional to the rate of heat flow through the wafer. The heat flux transducers were installed using masking tape on the interior surfaces of both the north-facing and the west-facing walls at the locations either midway between wood studs or furring strips, or over these wall framing members.

Calibration of the heat flux transducers was accomplished prior to the installation using a standard guarded hot plate apparatus described in references [5, 6]. The heat flux transducers to be calibrated were sandwiched between two insulation boards installed next to the hot and cold plates of the apparatus, and exposed to a uniform heat flux at the mean temperature corresponding to that observed during the field measurements. After a 24-hour conditioning period, the sensitivity of each heat flux transducer was determined by dividing the measured millivolt output by the applied heat flux. The accuracy of the transducer calibration was estimated to be within $\pm$ 1%.

The portable calorimeter was developed at the Building Research Division of the National Research Council of Canada for in-situ measurement of heat flow through building envelopes [1]. Brown and Schuyler [2] used this apparatus to quantify heat transmission through wood frame walls of single-family houses. In order to measure the thermal resistance of wall structures, two different size portable calorimeters, similar to that employed by Brown and Schuyler [2] were designed, fabricated and instrumented. These portable calorimeters were used to determine the overall thermal performance of masonry and metal panel faced exterior walls of eight office buildings situated in different geographical and various climatic regions [7-9].

The calorimeter is a five sided insulated box with an open side that is sealed against the building wall under test. The construction details of the smaller size portable calorimeter are given in figure 1. The calorimeter walls were constructed from two layers of 2 in. (50 mm) thick aluminum foil faced, semi-rigid glass fiber insulation boards glued

together with the foiled side exposed. The four exterior sides of the calorimeter were covered by 1/2 in. (13 mm) plywood to provide structural support. The back wall had an overall thermal resistance of R 17.4 $ft^2 \cdot h \cdot {}^oF/Btu$ ($3.06\ m^2 \cdot K/w$). In order to make an air-tight seal between the calorimeter and the wall to be tested, a rubber foam gasketing material was installed along the edges of the open face of the calorimeter box. The sizes of the metering area of these two calorimeters were 31 x 35 in. (0.79 x 0.89 m) and 46 x 75 in. (1.17 x 1.19 m), respectively.

Each portable calorimeter contained an electric resistance heater with an electrical power consumption rate of 90 W for the small size, and 140 W for the large one. A thermopile, with its many thermocouple junctions distributed evenly and attached on both the interior and the exterior surfaces of the calorimeter back wall, was used to monitor the temperature differential across the calorimeter wall.

The automatic measurement and control system used for the calorimeter is shown schematically in figure 2. A voltage controller, using the thermopile output as the feedback variable, was employed to control the electrical energy supplied to the electric heater by maintaining a zero temperature difference between the inside and the outside surfaces of the calorimeter wall. A safety thermostat with a sensing element located in the calorimeter box controlled the temperature of air inside the calorimeter within the safety limit. The total electric energy consumed by the heater was measured with a watt-hour meter equipped with an optoelectronic device consisting of a light-emitting diode and a detector. This device generated an electric pulse each time 1.8 watt-hour of electric energy was consumed. These pulses were totaled by an electronic counter. Since the heat losses through the box walls and the edges that contacted the metered surface were approximately nulled to zero, the electrical energy supplied to the heater was essentially equal to the heat flow through the metered area.

Bead shaped thermistors were used to measure the temperatures of the outdoor and indoor air in the vicinity of heat flux transducers, and of the air inside the portable calorimeters. Each thermistor consisted of an external network with a fixed precision resistor. This temperature sensor produced an output voltage proportional to the temperature over a temperature range between -22 to 122^oF (-30 to 50^oC). The measurement accuracy of the thermistors was $\pm$ 0.5^oF (0.3^oC), based on the technical data provided by the manufacturer.

In-situ heat flow measurements were conducted on the exterior walls of the six test buildings from January to March, 1985. The duration of each test ranged from 7 to 12 days. The indoor temperature of each test building was thermostatically controlled at 69 $\pm$ 0.6^oF (20.6 $\pm$ 0.3^oC). During the field measurements, the heat flux transducers were attached to the internal surfaces of the north- and west-facing walls in each building using masking tape. A stud finder was used to ensure that every heat flux transducer was mounted either on wall framing members or midway between them. The open side of the calorimeter was sealed against the inner surface of the test wall using duct tape. The outdoor air temperature was measured with a thermistor installed on a bracket extending 8 in. (203 mm) from the outer surface of the north-facing wall. Each thermistor used for measuring indoor temperatures was secured with its sensing element positioned 6 in.

(152 mm) from the wall surface being measured. The output signals from the heat flux transducers, the electric pulses from the watt-hour meters used with the portable calorimeters, and the thermistors were recorded simultaneously by a micro-computer based data acquisition system. This system was capable of recording data from 15 thermistors, 15 heat flux transducers and 6 calorimeters simultaneously. Continuous readings of all transducers were taken at two second intervals. The computer averaged the readings over one hour intervals, and recorded the hourly averages on a floppy disk for further processing and analysis.

4. TEST RESULTS

4.1 FIELD MEASUREMENTS WITH TEST BUILDINGS

Table 2 presents thermal resistance data for sections of the north-facing wall in each test building as measured with both the large and small portable calorimeters, and with the heat flux transducers. Heat flux was measured at locations where wall framing members exist and also at locations midway between framings. The predicted steady-state resistance and the measured results from the guarded hot box for wall specimens with the identical construction as the building walls are also shown in Table 2. All of the measured data from the in-situ methods are mean values of the data collected over a 24-hour period for 6 to 12 consecutive days. Error due to transient effect can generally be minimized by averaging the air temperature and surface heat flux data over a 24-hour period. The wall thermal resistance was determined by dividing the temperature difference between the indoor and the outdoor air across the wall structure by the measured heat flow rate. Since there are no wall framing members contained within the exterior walls built either from logs or masonry construction insulated with inside mass, no data are presented.

The average R-value measured by heat flux transducers and the predicted steady-state thermal resistance value were calculated using both the zone and the series resistance method [10]. The overall thermal resistance value including the correction for wall framing effect can be calculated from the following equation:

$$R^{-1} = R_F^{-1} \text{ (\% framing)}/100 + R_C^{-1} \text{ (100 - \% framing)}/100 \qquad (1)$$

where R is the average thermal resistance value, R_F is the thermal resistance value measured at the framing member, and R_C is the resistance value measured at the cavity between framings. For computing the predicted values, the published data on thermal properties of the building materials involved were used along with the assumed thermal resistance values of 0.68 $ft^2 \cdot h \cdot {}^oF/Btu$ (0.12 $m^2 \cdot K/W$) and 0.17 $ft^2 \cdot h \cdot {}^oF/Btu$ (0.03 $m^2 \cdot K/W$) for the air films at the warm and cold wall surfaces. These film resistances represent conditions when the room side of the exterior wall is exposed to still air and the exterior side is subject to a 15 mph (6.7 m/s) wind.

As illustrated in Table 2, there is a fairly good agreement existing between the measured wall thermal resistance values and the predicted results. The percentage deviation between the predicted values and the experimental results obtained from the portable calorimeters is found to vary from 4 to 20% with an average of 12%. The wall resistance values measured with heat flux transducers deviated from the predicted values by

an average of 13% with a range covering between 6% and 28%. The large differences betweem the predicted and measured values occurred for insulated and uninsulated masonry walls. Possible reasons for the discrepancy include the uncertainties in the handbook values for thermal resistances of the building components and the transient effects of massive thermal masses for these building walls. In general, the thermal resistances determined by the small sized calorimeter are lower than those measured with the large calorimeter because its metering wall area contains approximately 30% more wall framing area for framed walls. This results in increased heat flow due to the presence of these conductive framing members.

The air-to-air thermal resistance measured with a guarded hot box apparatus for wall specimens having the same construction as the walls of the six test buildings are also presented in Table 2. Six 6 x 6 ft. (1.8 x 1.8 m) wall specimens were tested in accordance with standard hot box test procedures by an independent test laboratory. Each test wall was placed between an environmental chamber and a metering box, which was maintained at 70°F (21°C) inside a guarded hot chamber. The cold chamber was controlled at 5°F (-15°C) until the test wall achieved thermal equilibrium, and then raised to 35°F (2°C) for the six hour test. The airflow rates parallel to the warm-side and cold-side surfaces of the test wall were 0.7 mph (0.3 m/s) and 0.4 mph (0.2 m/s), respectively. Thermocouples were used to measure the hot and cold test wall surface temperatures, and the temperatures of air in the proximity of the test wall on the hot and cold sides. The heat flow through the test wall was determined by measuring the total electrical power input to the heater and the fan in the metering box using precision resistor networks. Overall thermal resistance of each test wall was derived from these wall surface temperature and electrical energy consumption data. The air-to-air thermal resistance values in Table 2 were based on the results of the calibrated hot box measurements along with the estimated air film thermal resistances of 0.68 $ft^2 \cdot h \cdot {}^oF/Btu$ (0.12 $m^2 \cdot K/w$) at the warm surface and 0.40 $ft^2 \cdot h \cdot {}^oF/Btu$ (0.07 $m^2 \cdot K/w$) at cold surface.

Table 2 shows that the experimental values obtained by the guarded hot box are in good agreement with the thermal resistance results derived from steady-state thermal resistance predictions. The average percent deviation between the predicted and measured results from the guarded hot box for each wall was approximately 8%. The average indoor and outdoor air temperatures recorded during the field thermal resistance measurements are presented in Table 3 along with the observed air temperatures at the warm and cold sides of the wall structures measured with the laboratory guarded hot box. The air temperature difference across the building walls during the in-situ measurements ranged widely from approximately 16 to 47°F with an average of 33°F.

4.2 LABORATORY MEASUREMENTS WITH DOUBLE-STUDDED WALL

In order to check the overall performances of the portable calorimeters and the heat flux transducers, and assess their accuracy levels, in-situ thermal resistance measurements were also performed on a well-insulated double-studded wall installed in the calibrated hot box apparatus at the National Bureau of Standards, Gaithersburg, MD. This series of tests allowed comparison of the thermal resistances measured using the calorimeters and transducers with those determined with the calibrated hot

box test. The wall specimen measuring 15 x 8 ft. (4.57 x 2.44 m) high and 6.75 in. (172 mm) in thickness, had a 0.002 in. (0.051 mm) thick polyethylene vapor barrier and 1/2 in. (12.7 mm) gypsum wallboard on the inside, a double layer of R-11 $ft^2 \cdot h \cdot {}^oF/Btu$ (1.94 $m^2 \cdot K/w$) glass fiber insulation installed in the cavities formed between nominal 2 x 3 in. (51 x 76 mm) wood studs placed 16 in. (406 mm) on center, and a 3/4 in. (19 mm) thick isocyanurate sheathing and a 1/2 in. (12.7 mm) wood siding on the outside. The construction details of the wall specimen, and the locations of the portable calorimeters and the heat flux transducers are shown in figure 3. In order to accommodate the width of wood stud used, the glass fiber blanket insulation in the stud cavities was compressed from 3.5 in. (89 mm) to 2.5 in. (64 mm) thickness. The steady-state thermal resistance of this double-stud wall was calculated using the series resistance method [10], and found to be 23.75 $ft^2 \cdot h \cdot {}^oF/Btu$, in which a thermal resistance value of 8.77 $ft^2 \cdot h \cdot {}^oF/Btu$ determined by the guarded hot plate apparatus was used for the compressed glass fiber blanket insulation [11].

The NBS calibrated hot box can evaluate the thermal performance of composite wall specimens having dimensions of up to 10 ft. (3.05 m) wide by 15 ft. (4.57 m) high by 2 ft. (0.61 m) thick. This apparatus is capable of providing steady-state temperatures ranging from -40 to 65°C for the climatic chamber, and from 10 to 65°C for the metering chamber. The construction of this test facility has been described in detail in references [11, 12]. During the laboratory measurements, the double-stud wall specimen was held in the test frame with its outer wall surface sealed against the climatic chamber in which the temperature was either maintained at a constant value or changed with time in a controlled manner to simulate outdoor weather conditions. The interior side of the test wall was exposed to ambient air in a large environmental chamber controlled at a fixed temperature to represent indoor conditions. Both the large and small sized portable calorimeters were sealed tightly against the inside surface of the test wall by the duct tape and rubber foam gasket installed at the edges of the calorimeters. The heat flux transducers were taped on the inside surface of wall areas over both the wood studs and the thermal insulation filled cavities between studs as shown in figure 3.

Two tests were performed, one test with the temperature of air in the climatic chamber held at a constant value of 34.4°F (1.3°C), and the other test with the chamber air temperature varied periodically to simulate diurnal air temperature conditions. The apparatus was programmed to control the temperature of the air within the climatic chamber according to the following cosine function:

$$T = 16.2 \cos (\pi t/12 - \pi/2) + 42.8 \qquad (2)$$

where T is the climatic chamber air temperature in °F and t is the time in hours.

Table 4 presents the average wall resistance values measured by the portable calorimeters and heat flux transducers, and the air temperatures as determined by thermistors, for the double-stud wall for both steady-state and dynamic climatic conditions. For the test wall exposed to a periodic temperature variation, it was found after completion of the test that the duration time for each temperature cycle was 23.33 hours. The values for constant outdoor temperature in the table are averages over two

consecutive 24-hour cycles and the values for the dynamic climatic condition are averages over three successive 23-hour cycles. The wall thermal resistance value measured by the calibrated hot box and the corresponding predicted value calculated by the series resistance method are also listed in Table 4 for comparison. The resistance value determined by the calibrated hot box was obtained with the apparatus operated in a steady-state mode with the test wall in the test frame clamped between the metering chamber and the climatic chamber. The thermal resistance value obtained from the calibrated hot box measurements included estimated air film resistances of 0.68 $ft^2 \cdot h \cdot {}^oF/Btu$ (0.12 $m^2 \cdot K/w$) at warm surface and 0.36 $ft^2 \cdot h \cdot {}^oF/Btu$ (0.06 $m^2 \cdot K/w$) at the cold surface based on a measured air velocity of 1.9 mph (0.8 m/s).

Inspection of Table 4 indicates that the measured thermal resistance values are generally in good agreement with the predicted results. The wall resistance values determined by the large and small portable calorimeters, the heat flux transducer and the calibrated hot box apparatus are within 6, 1, 6 and 4 percent of the corresponding predicted value, respectively. Based on the results of these two laboratory tests involving in-situ measurements. The dynamic climatic condition gave a slightly smaller value of wall resistance than given by the steady-state condition. This is probably a result of the transient effects of varying temperature on thermal conductivities of component materials in the test wall. More test data are needed to evaluate these preliminary experimental observations.

5. COMPARISON OF TEST RESULTS BETWEEN IN-SITU MEASUREMENTS AND THE HOT BOX METHOD

The thermal resistance values measured with the portable calorimeters for the exterior walls of the six test buildings and the well insulated double-stud wall are plotted in figure 4 against the resistance values determined by the hot box for the identical wall sections. A similar plot for comparing the thermal resistance results from heat flux transducer measurements with values obtained in the laboratory using the hot box test is shown in figure 5. These plots show that a good correlation exists between the wall resistance results obtained from the in-situ measurements and the laboratory hot box data, because all the data points lie close to the line of perfect agreement. The percentage deviation between the wall resistances measured with the portable calorimeter and the resistance values determined by the hot box apparatus was found to vary between 1% to 20% with an average of 9% for the seven walls. The greater departures were found in the thermally massive insulated walls. The thermal resistance values obtained from in-situ measurements with heat flux transducers departed from the hot box data by an average of 8% with a range varying between 1% and 15%.

6. THE VARIABILITY OF MEASURED THERMAL RESISTANCE VALUES

In order to determine the extent of variation in the values measured with the portable calorimeters and heat flux transducers, calculations of the coefficient of variation were made with the daily averaged wall resistance data obtained from field and laboratory measurements. The coefficient of variation is equal to the percentage of the ratio of the standard deviation to the mean value. The results of the statistical analysis for each wall structure are summarized in Table 5. It can be noted that there is a wide

variation in the measurement period for the field tests, from 3 to 12 days. The measurement periods of several tests were shortened due to the occurence of unseasonably warm weather, with the outdoor temperature greater than 60°F (15.6°C) for a few days. In addition, some difficulties were experienced with the temperature controller of the heating system during the course of the test. Excluding one test that had considerable variability of the measured resistance values attributed to malfunction of the thermostat (insulated masonry wall with outside mass), the coefficients of variation, which are a measure of the degree of variability of the thermal resistance data within a single instrument, for the large and small calorimeters, and the heat flux transducer are found on the average to be 3.8%, 5.8% and 4.3%, respectively.

Table 6 lists the numbers of heat flux transducers installed between framing members and over the wall framings, the range of measured wall resistance values, and the coefficient of variation of the measured resistance results between different heat flux transducers for each exterior wall. As illustrated in the table, the coefficient of variation varies significantly from wall to wall depending upon the wall mass and thermal insulation property. These coefficients of variation were found to range from 0.2 to 16% with an average of 6%. This average value representing the between-transducer variability is slightly greater than the corresponding within-transducer variability. However, all of the heat flux transducers may be considered to be essentially in agreement because the difference between these two variability values is small.

7. CONCLUSIONS

Both the portable calorimeter and heat flux transducer were found to be reliable and practical tools for thermal resistance measurements of exterior envelopes in the field. The performance evaluation of both instruments involved the exterior walls of six thermal mass test houses and a comparative test of calibrated hot box measurements and the in-situ methods in a laboratory controlled environment. The exterior walls tested had thermal resistance values ranging from 3.6 to 22.8 $ft^2 \cdot h \cdot {}^{\circ}F/Btu$ (0.6 to 4.0 $m^2 \cdot K/W$) and wall mass varying from 4.2 to 83 lb/ft^2 (21 to 405 kg/m^2). The portable calorimeter can measure a sufficiently large wall area to provide a representative bulk performance of the wall with a minimum disturbance to the heat transmission through the wall. Due to the dynamic response of an exterior wall to diurnal variations in heat flow caused by outdoor air temperature variation, a sufficiently long measurement period, especially for a massive insulated wall system, is required to obtain reliable thermal resistance data using the in-situ methods. Portable calorimeters and properly calibrated heat flux transducers can produce wall thermal resistance values with an average deviation of less than 9% in comparison with values obtained in the laboratory using a calibrated hot box. The extent of variability in the wall resistance values measured by a single calorimeter was found to range from 0.3 to 9% with an average of 3.8%, and varying from 0.3 to 7% with a mean of 4.3% for the heat flux transducer measurements. To determine the overall thermal resistance value for a framed wall, heat flux transducers must be mounted on wall areas backed by both framing members and cavities between the framings. Corrections then have to be made accordingly for the effect of framing members. Based on the data from the tests, the variation in the measured

wall resistance values among the heat flux transducers varied between 0.2 and 16% with a mean value of 6%.

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Table 1

Construction Details of Exterior Walls
of Test Buildings

No. 1	Insulated Lightweight Wood Frame	5/8 in. (16 mm) exterior plywood, nominal 2 x 4 in. (50 x 100 mm) wood studs placed 16 in. (410 mm) on center with R-11 $h \cdot ft^2 \cdot {}^\circ F/Btu$ (R-1.94 $m^2 \cdot K/W$) blanket glass insulation installed between the studs, a 0.002 in. (0.05 mm) polyethylene film and 1/2 in. (13 mm) gypsum board.
No. 2	Uninsulated Lightweight Wood Frame	Same as No. 1, except no insulation in the stud cavities.
No. 3	Insulated Masonry (Outside Mass)	4 in. (100 mm) face brick, 4 in. (100 mm) 2-core hollow concrete block at 105 lb/ft^3 (1680 kg/m^3), a 1/4 in. (6.4 mm) air space, 2 in. (51 mm) thick extruded polystyrene foam insulation placed between 1-1/2 x 2 in. (38 x 51 mm) wood furring strips placed 24 in. (610 mm) on center, a 0.002 in. (0.05 mm) polyethylene film, and 1/2 in. (13 mm) gypsum board.
No. 4	Uninsulated Masonry	8 in. (200 mm) 2-core hollow concrete block of 105 lb/ft^3 (1680 kg/m^3), a 3/4 in. (20 mm) air space created by 2 x 1 in. (50 x 25 mm) wood furring strips placed 16 in. (410 mm) on center, a 0.002 in. (0.05 mm) polyethylene film, and 1/2 in. (13 mm) gypsum board.
No. 5	Log	7 in. (180 mm) square lodge-pole-pine logs (butt-jointed with a compressible foam backer-rod and a caulking compound applied to interior and exterior joints).
No. 6	Insulated Masonry (Inside Mass)	4 in. (100 mm) face brick, 3-1/2 in. (89 mm) perlite loose-fill insulation in cavity, 8 in. (200 mm) 2-core hollow concrete block at 105 lb/ft^3 (1680 kg/m^3), and a 1/2 in. (13 mm) plaster.

Table 2

Comparison of Wall Thermal Resistances Measured with Portable Calorimeters (PC) and Heat Flux Transducers (HFT) to Corresponding Predicted Values and Measured Results from Guarded Hot Box

		Thermal Resistance ($ft^2 \cdot h \cdot {}^oF/Btu$)						
		Measured Value						
		PC		HFT				
Construction	Mass (lb/ft^2)	Large	Small	Between Framings	At Framing	Avg.	Predicted Value	Guarded Hot Box
Insulated wood frame	4.4	11.43	10.14	14.27	10.41	13.79	11.91	12.22
Uninsulated wood frame	4.2	3.55	3.34	3.43	4.01	3.48	3.14	3.60
Insulated masonry with outside mass	64.0	11.01	13.31	15.15	9.39	14.59	13.77	13.69
Uninsulated masonry	42.0	4.41	4.18	4.95	5.08	4.97	3.89	4.63
Log	17.0	10.08	9.83	10.27	-	10.27	9.60	10.33
Insulated masonry with inside mass	83.0	10.20	9.53	14.32	-	14.32	12.65	12.42

Note: 1 $ft^2 \cdot h \cdot {}^oF/Btu = 0.176\ m^2 \cdot K/W$
1 $lb/ft^2 = 4.882\ kg/m^2$

Table 3
The Measured Average Air Temperatures Across Wall Structures During Field and Laboratory Wall Thermal Resistance Measurements

Wall Construction	Air Temperature, °F: In-Situ Measurements: Indoor	Air Temperature, °F: In-Situ Measurements: Outdoor	Air Temperature, °F: Guarded Hot Box: Warm Side	Air Temperature, °F: Guarded Hot Box: Cold Side
Insulated wood frame	69.2	45.2	74.9	32.0
Uninsulated wood frame	70.3	43.5	77.9	33.6
Insulated Masonry with outside mass	69.9	54.2	73.3	24.2
Uninsulated masonry	74.1	27.3	83.2	31.4
Log	68.4	26.8	83.6	37.4
Insulated Masonry with inside mass	68.2	26.3	76.5	23.9

Note: $^{o}C = 5/9\ (^{o}F - 32)$

Table 4

Comparison of Measured and Predicted Thermal Resistances of Well-Insulated Double-Stud Wall Under Steady-State and Dynamic Climatic Conditions

	Air Temp. (°F)		Thermal Resistance ($ft^2 \cdot h \cdot {}^oF/Btu$)							
				Measured Value					
				Calorimeter		Flux Transducer			
Climatic Condition	Warm Side	Cold Side	Predicted Value	Large	Small	Between Studs	At Stud	Avg.	Calibrated Hot Box
Steady-State	69.5	34.4	23.75	25.25	24.07	26.37	20.98	25.16	22.84
Dynamic	70.0	42.1*	-	23.86	23.56	25.30	20.47	24.23	-

Note: $^oC = 5/9\ (^oF - 32)$
$1\ ft^2 \cdot h \cdot {}^oF/Btu = 0.176\ m^2 \cdot K/W$

* The average value of periodically varying air temperatures ranging from 26.5 to 52.2°F

Table 5
The Variability of Wall Thermal Resistance Values Measured by a Single Portable Calorimeter or Heat Flux Transducer

Wall Assembly	Portable Calorimeter				Heat Flux Transducer		
	Large		Small		Test	C.V.* (%)	
	Duration (day)	C.V.* (%)	Duration (day)	C.V.* (%)	Duration (day)	Between Framings	At Framing
Insulated wood frame	11	4.14	8	7.33	8	7.23 (7.2-7.3)	7.01 (6.6-7.4)
Uninsulated wood frame	9	3.05	7	3.19	7	2.20 (2.2-2.4)	2.96 (2.5-3.4)
Insulated masonry with outside mass	10	9.09	3	20.6	3	15.2 (13.4-18.2)	15.3 (14.9-15.7)
Uninsulated masonry	12	3.13	5	7.67	5	7.02 (6.6-7.5)	7.92
Log	10	7.12	10	7.76	10	6.42 (6.3-6.5)	-
Insulated masonry with inside mass	4	1.80	3	10.2	4	4.94 (4.1-5.8)	-
Double-stud wood frame:							
Steady-state condition	2	0.34	2	3.44	2	0.27 (0.03-0.4)	0.74 (0.1-1.4)
Dynamic case	3	2.03	3	1.30	3	1.85 (0.7-3.2)	2.83 (1.9-3.8)

*Coefficient of variation = (Standard Deviation/Mean) x 100.

Table 6
The Variations in the Measured Thermal Resistance Values Among Heat Flux Transducers

Wall Assembly	Between Wall Framings			At Wall Framing		
	No. of Sensors	Range of R-Values ($ft^2 \cdot h \cdot {}^oF/Btu$)	Coefficient of Variation (%)	No. of Sensors	R-Values ($ft^2 \cdot h \cdot {}^oF/Btu$)	Coefficient of Variation (%)
Insulated wood frame	2	13.8 - 14.7	4.56	2	10.2 - 10.6	3.06
Uninsulated wood frame	2	3.42 - 3.43	0.21	2	3.9 - 4.1	3.36
Insulated masonry with outside mass	3	13.5 - 16.2	9.63	2	9.1 - 9.7	4.52
Uninsulated masonry	2	4.7 - 5.2	6.00	1	5.1	-
Log	3	9.8 - 10.8	5.06			
Insulated masonry with inside mass	2	12.7 - 16.0	16.2			
Double-stud wood frame:						
Steady-state condition	3	24.8 - 29.4	10.1	2	20.6 - 21.3	2.29
Dynamic case	3	23.6 - 28.1	9.79	2	20.1 - 20.9	2.63

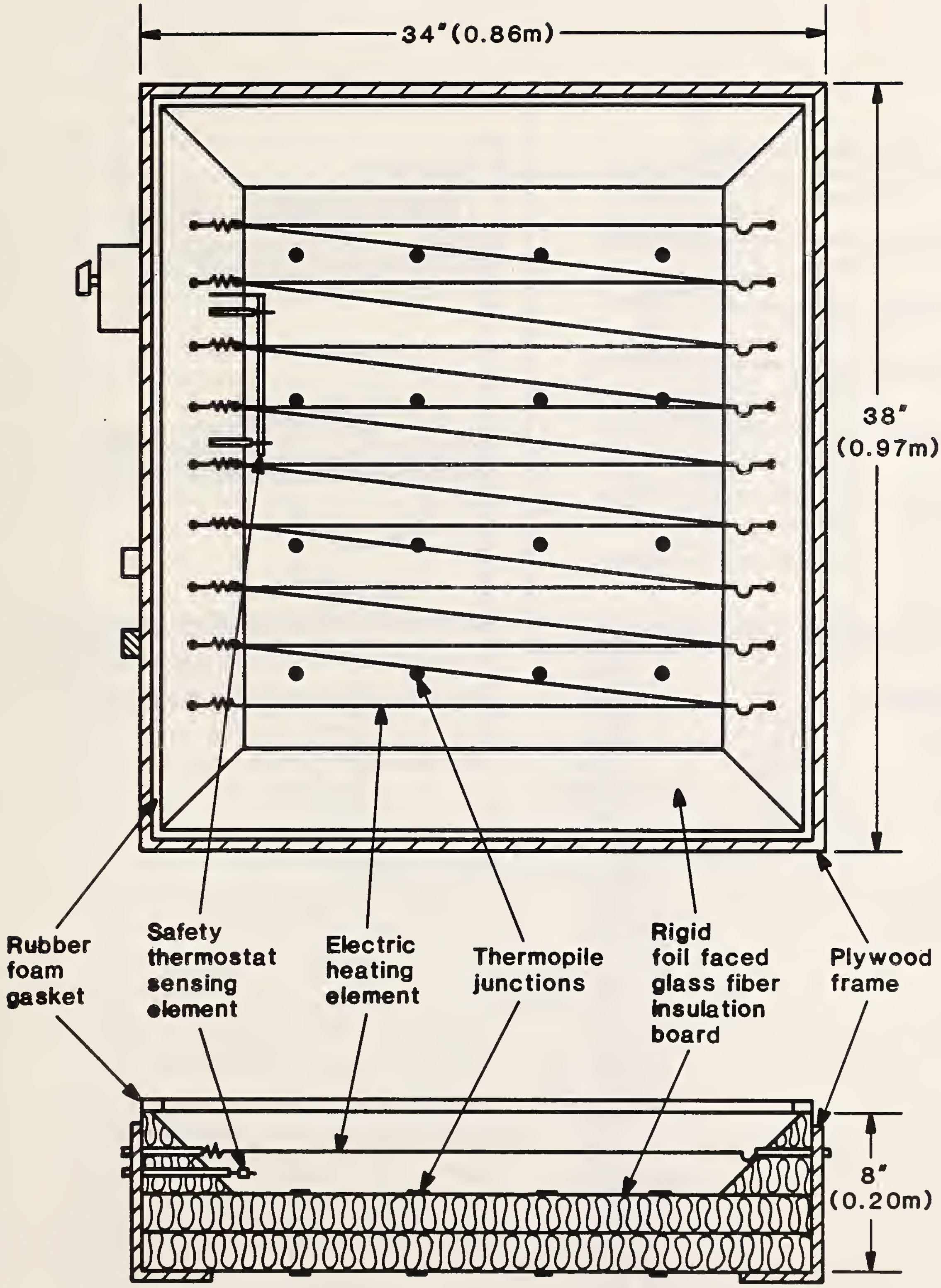

Figure 1. Construction Details of Small Sized
Portable Calorimeter

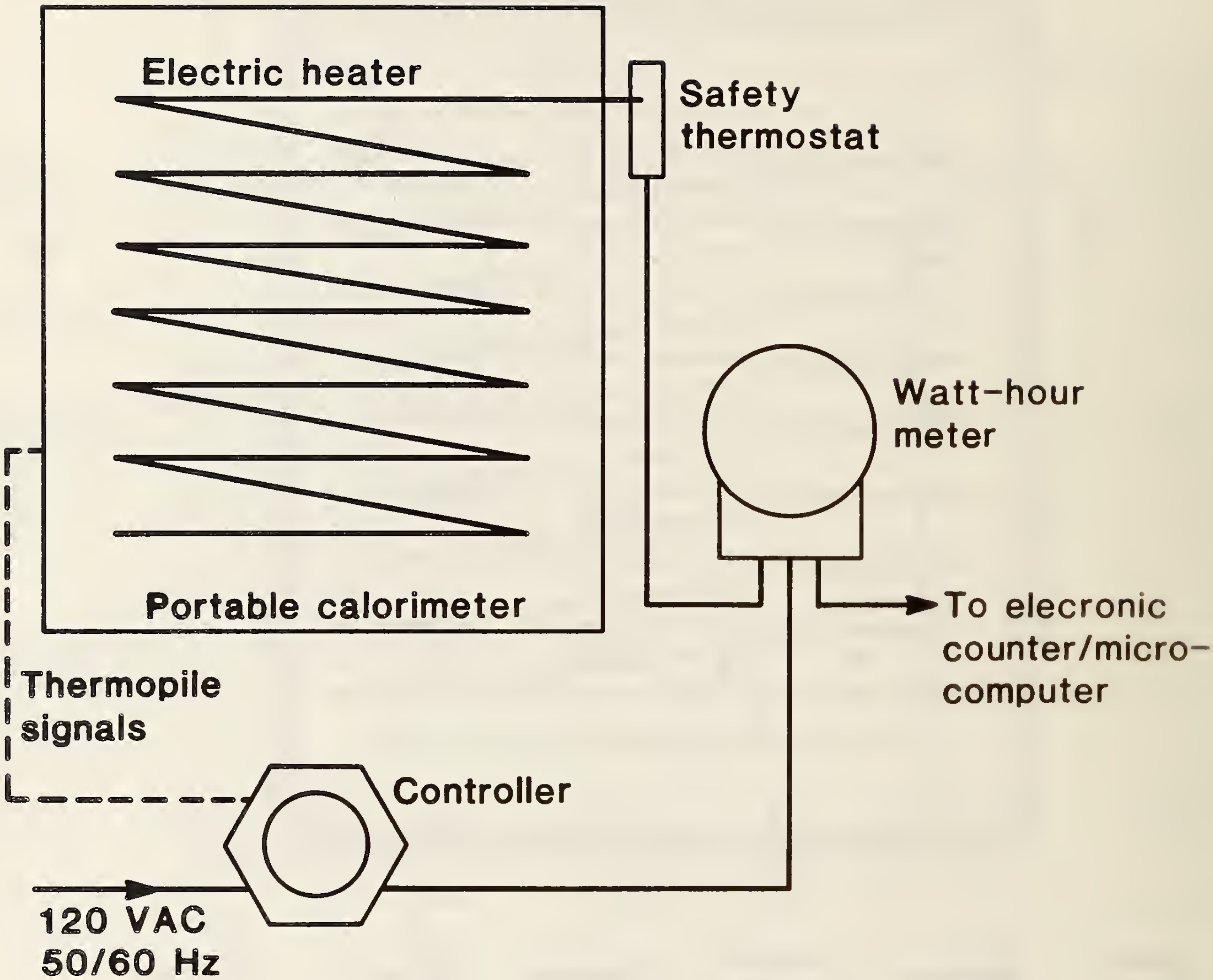

Figure 2. Schematic of the Measurement/Control System for the Portable Calorimeter

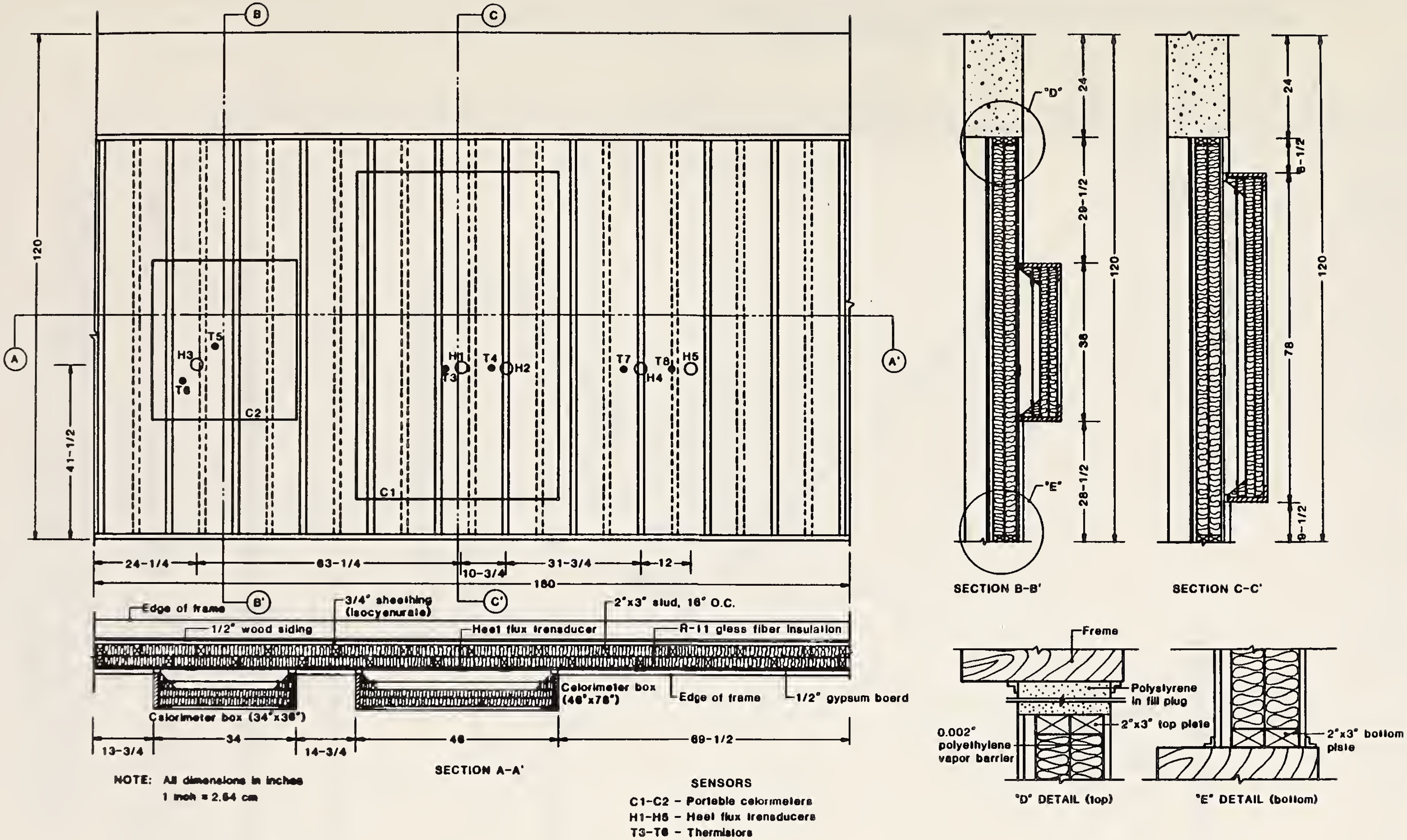

Figure 3. Construction Details and Sensor Locations on the Well Insulated Double-Stud Test Wall

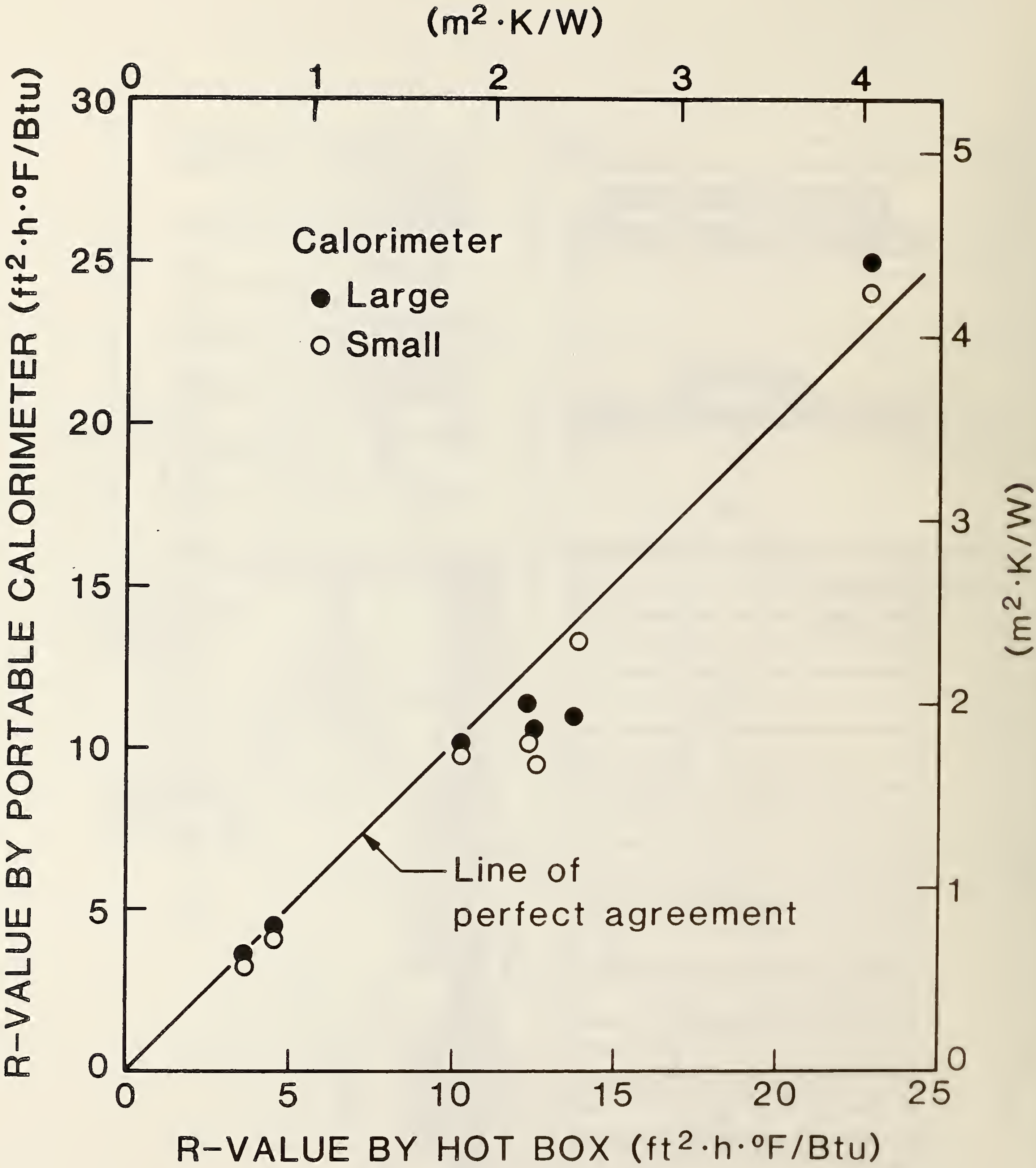

Figure 4. A Comparison Between the Wall Thermal Resistance Values Measured with Portable Calorimeter and the Values Obtained with the Calibrated Hot Box

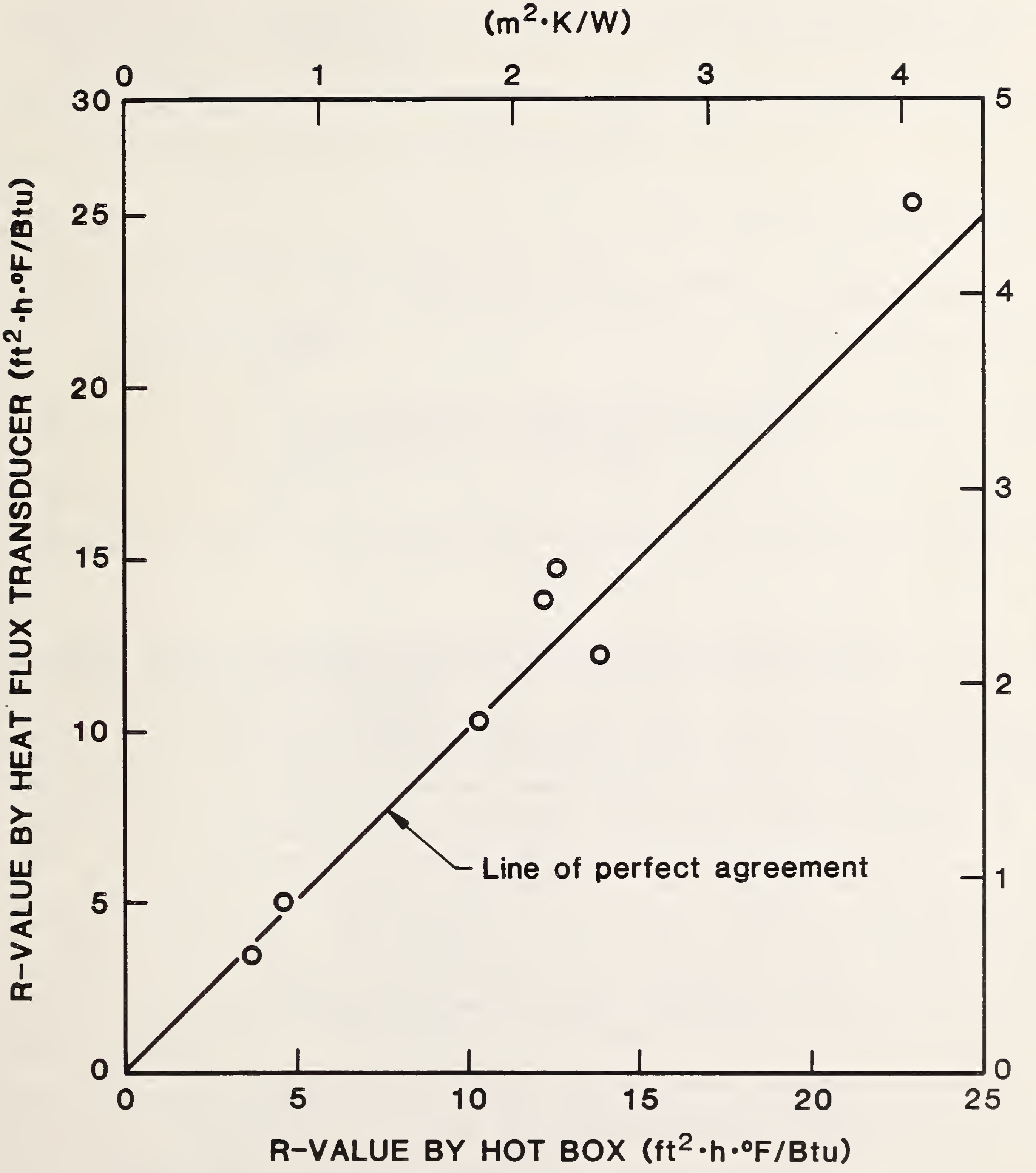

Figure 5. A Comparison of the Wall Resistance Values Measured by Heat Flux Transducers and the Calibrated Hot Box Data

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

A series of field and laboratory tests were conducted to evaluate the accuracy of in-situ thermal resistance measurement techniques. The results of thermal performance evaluation of the exterior walls of six thermal mass test houses situated in Gaithersburg, Maryland are presented. The wall construction of these one-room houses includes insulated light-weight wood frame, uninsulated light-weight wood frame, insulated masonry with outside mass, uninsulated masonry, log, and insulated masonry with inside mass. In-situ measurements of heat transfer through building envelopes were made with heat flux transducers and portable calorimeters. A sufficiently long period of measurements, depending on the thermal mass of wall structure, is needed to provide reliable thermal resistance data. The comparisons of the results from these field measurements with those derived from sections of the same wall structures tested in a guarded hot box facility in a laboratory are presented. A well-insulated, double-stud test wall was also tested under simulated thermal conditions including steady-state and periodically varying outdoor temperature using a calibrated hot box and the in-situ measurement procedures.

From these test results, the in-situ methods are shown to provide thermal resistance data within 9% of the hot box results. The extent of variability in wall resistance values measured by a single calorimeter or heat flux transducer is found to range from 0.3 to 9% with an average of 4%.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

building; exterior envelope; field test; heat flux; in-situ measurements; temperature; thermal resistance; portable calorimeter; wall

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